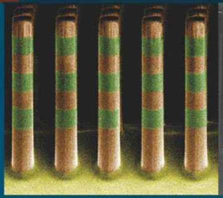
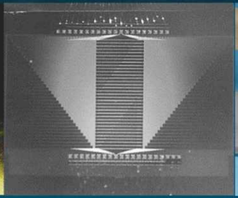
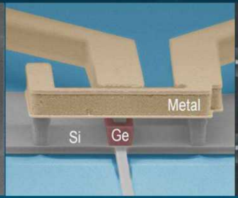
This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

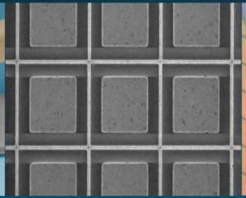
SAND2019-3360C

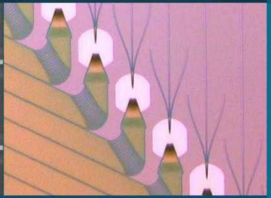
Propagation Loss in Crystalline Silicon Photonic Waveguides Due to Gamma Radiation











Nicholas Boynton, Michael Gehl, Christina Dallo, Andrew Pomerene, Andrew Starbuck, Dana Hood, Paul Dodd, Scot Swanson, Douglas Trotter, Anthony Lentine, Christopher DeRose

Photonic and Phononic Microsystems

National Security Photonics Center

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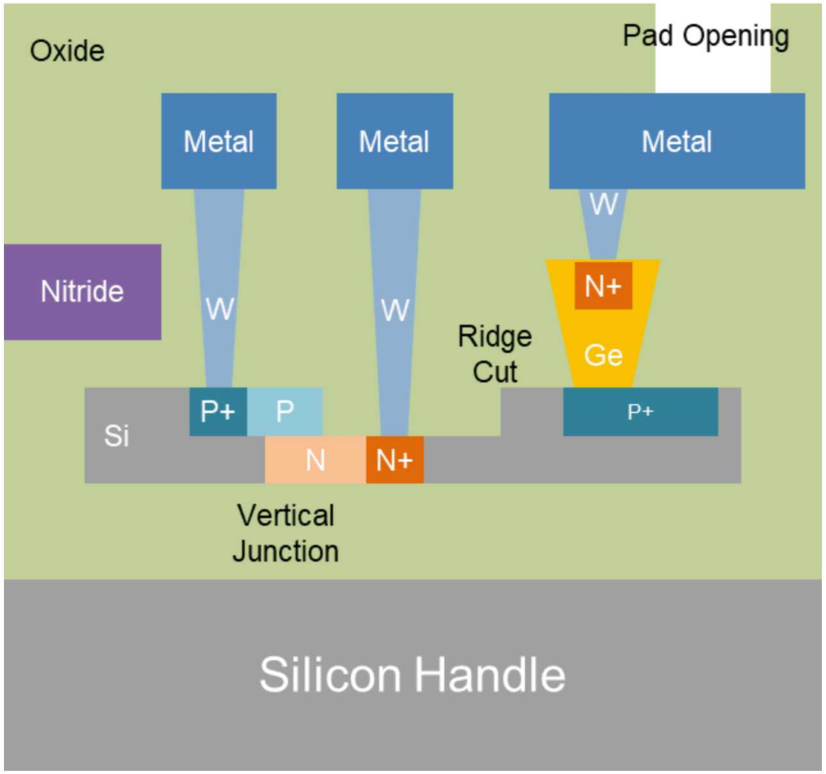
GOMACTech 2019, 26 March 2019

Silicon Photonics in Harsh Environments

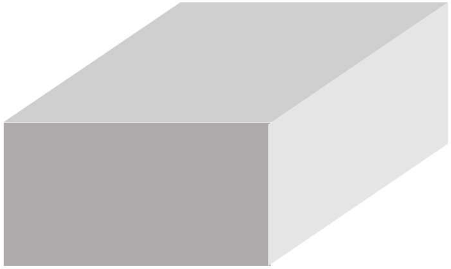
Silicon photonics
- CMOS compatible (integration), high bandwidth, low loss
- Applications include optical communication focal plane arrays (FPA's) and RF photonics

Harsh environments
- Space (low earth orbit (LEO))

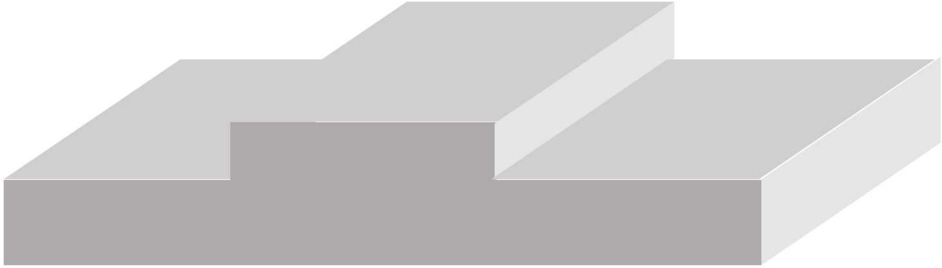
How do silicon waveguides of various geometries perform in these environments?



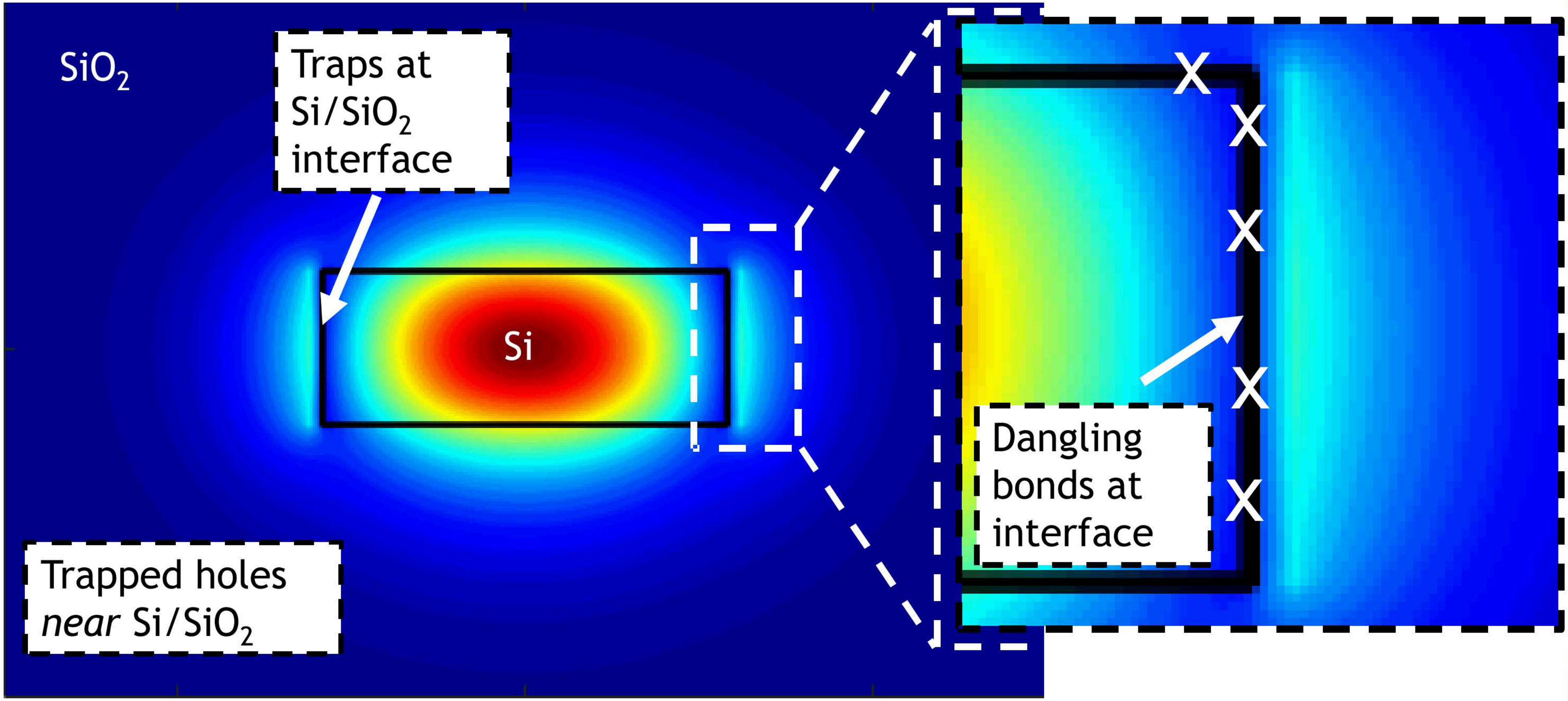
Fully Etched Strip Waveguide



Partially Etched Rib Waveguide



Effects of Gamma Radiation on Si/SiO_2 Structure



Free Carrier Absorption:

$$\delta\alpha_{Si}(\lambda = 1550\ nm) = 6 \times 10^{-18}\Delta N_H + 8.5 \times 10^{-18}\Delta N_e$$

M ZEILER, RADIATION-HARD SILICON PHOTONICS FOR FUTURE HIGH ENERGY PHYSICS EXPERIMENTS, 2017
N. M. JOHNSON ET. AL., CHARACTERISTIC ELECTRONIC DEFECTS AT THE SI-SIO2 INTERFACE, 1983
D. M. FLEETWOOD ET. AL., UNIFIED MODEL OF HOLE TRAPPING, 1/F NOISE, AND THERMALLY STIMULATED CURRENT IN MOS DEVICES, 2002
R. SOREF & B. BENNETT, ELECTROOPTICAL EFFECTS IN SILICON, 1987

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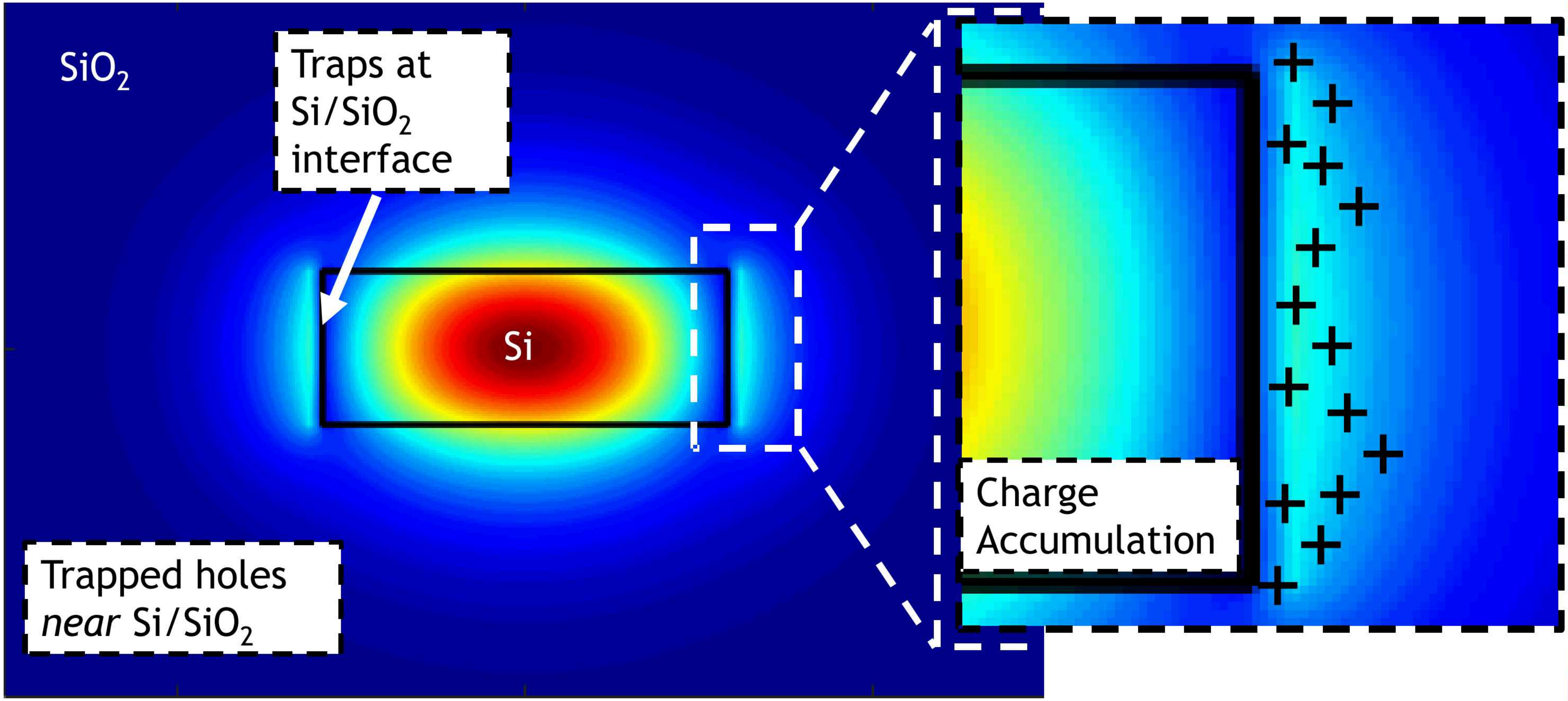

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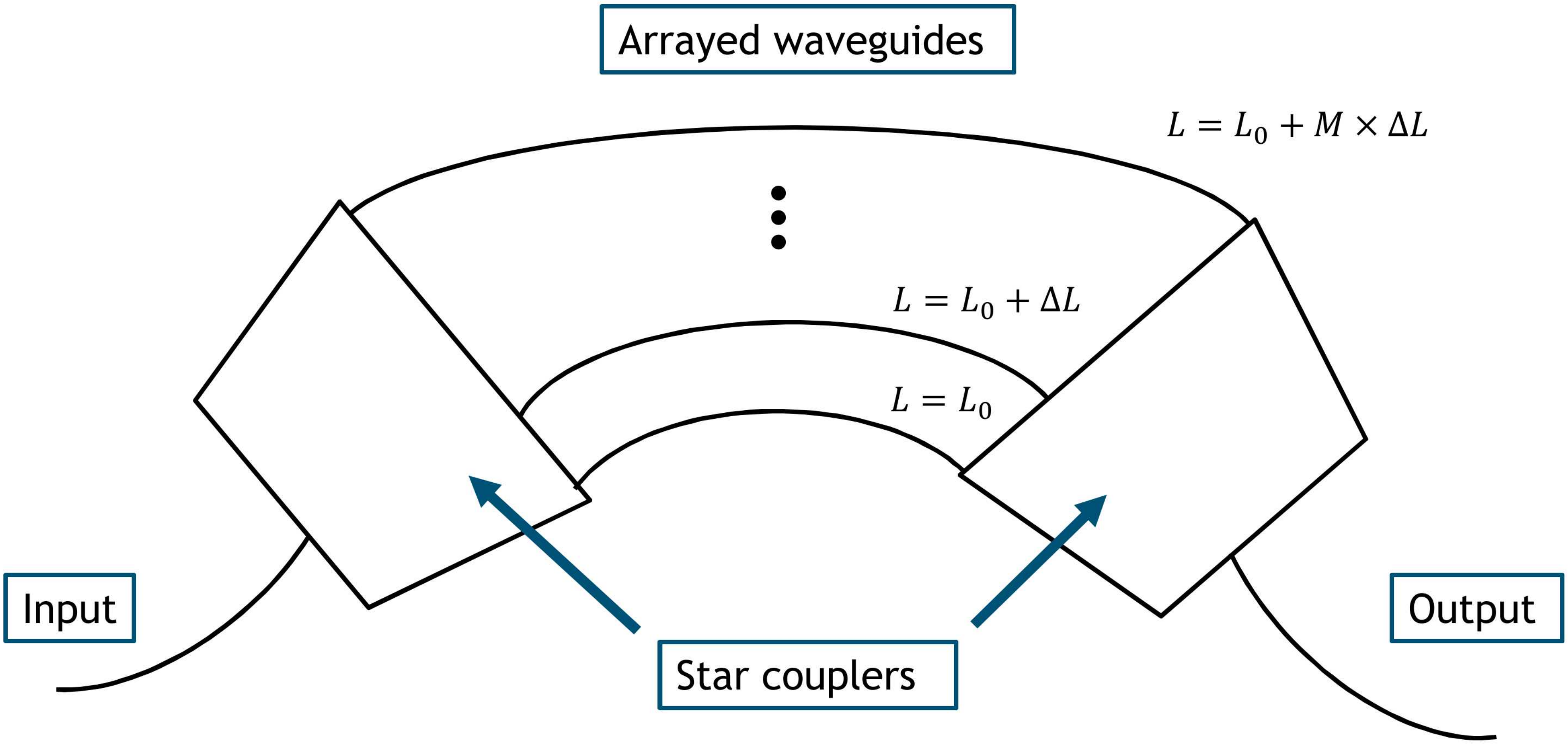
R. SOREF & B. BENNETT, ELECTROOPTICAL EFFECTS IN SILICON, 1987

Comparison With Previous Studies

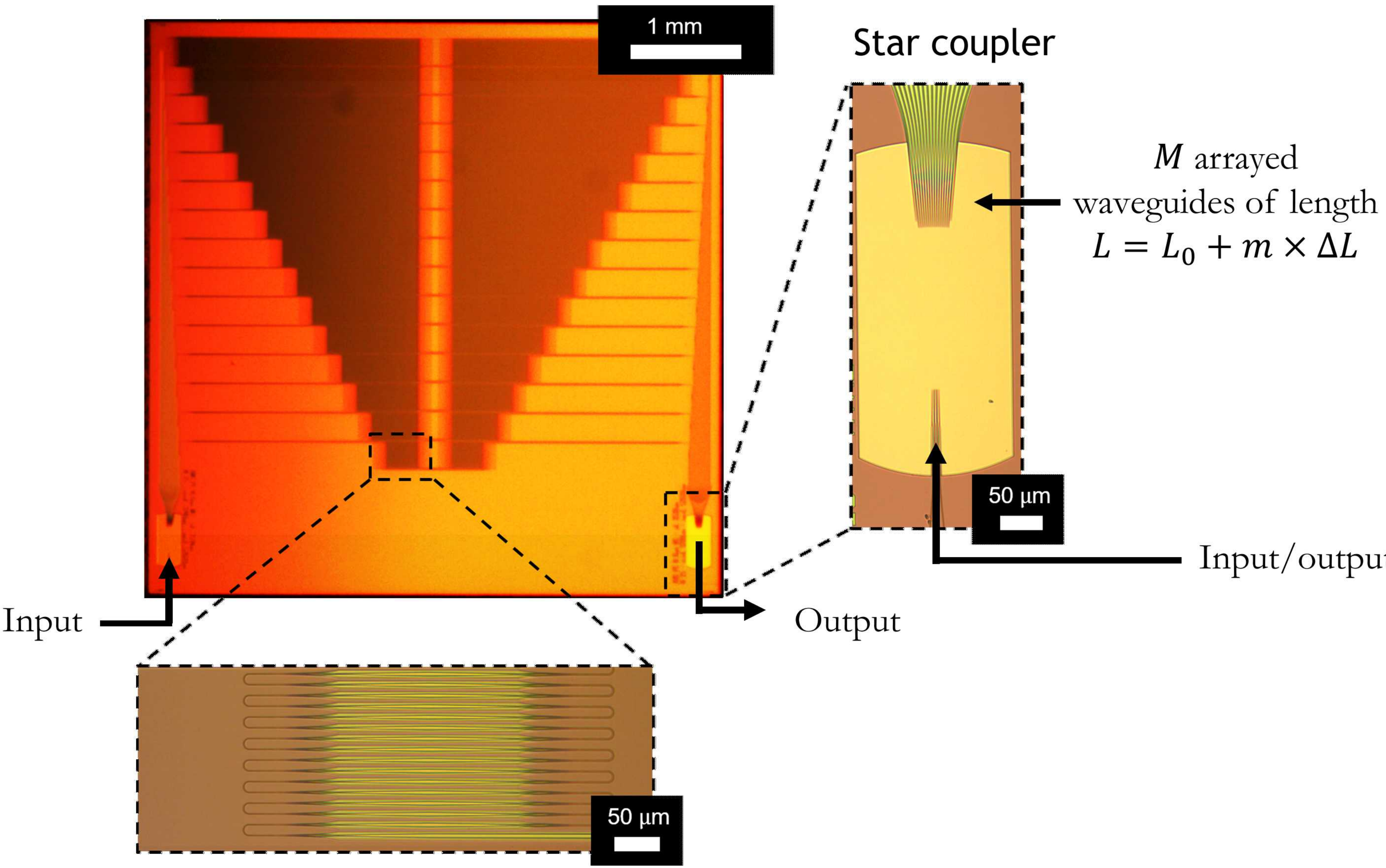
Source	Type of Radiation	Waveguide Core Material	Waveguide Cladding Material	Total Dose	Structure	Effect of Radiation on Loss	Loss Extraction Method
[1]	X-ray	Doped silicon (~10^{17} cm^{-3})	SiO_2	10 krad	Waveguides of different lengths	Decreased propagation loss	Cut-back
[2]	Gamma	Amorphous silicon	SiO_2	150 krad	Ring Resonator	None	Q-factor
[2]	Gamma	Amorphous silicon	Polymer	150 krad	Ring resonator	Increased propagation loss	Q-factor
[3]	Gamma	Silicon	SiO_2	10 krad	Bragg	None	Fabry-Perot
[3]	Gamma	Silicon	SiO_2	10 krad	Ring Resonator	None	Q-factor
[4]	Gamma	Silicon Nitride	SiO_2	10 Mrad	Ring Resonator	None	Q-Factor
[5]	**Gamma**	**Silicon**	**SiO_2**	**100 krad**	**Arrayed waveguide structure**	**Small increase in propagation loss**	**Swept wavelength interferometry**

[1] M. ZEILER ET. AL., RADIATION-HARD SILICON PHOTONICS FOR FUTURE HIGH ENERGY PHYSICS EXPERIMENTS, 2017
[2] S. GRILLANDA ET. AL., GAMMA RADIATION EFFECTS ON SILICON PHOTONIC WAVEGUIDES, 2016
[3] Z. AHMED AT. AL., ASSESSING RADIATION HARDNESS OF SILICON PHOTONIC SENSORS, 2018
[4] Q. DU ET. AL., GAMMA RADIATION EFFECTS IN AMORPHOUS SILICON AND SILICON NITRIDE PHOTONIC DEVICES, 2017
[5] THIS WORK

Arrayed Waveguide Structure for Loss Characterization

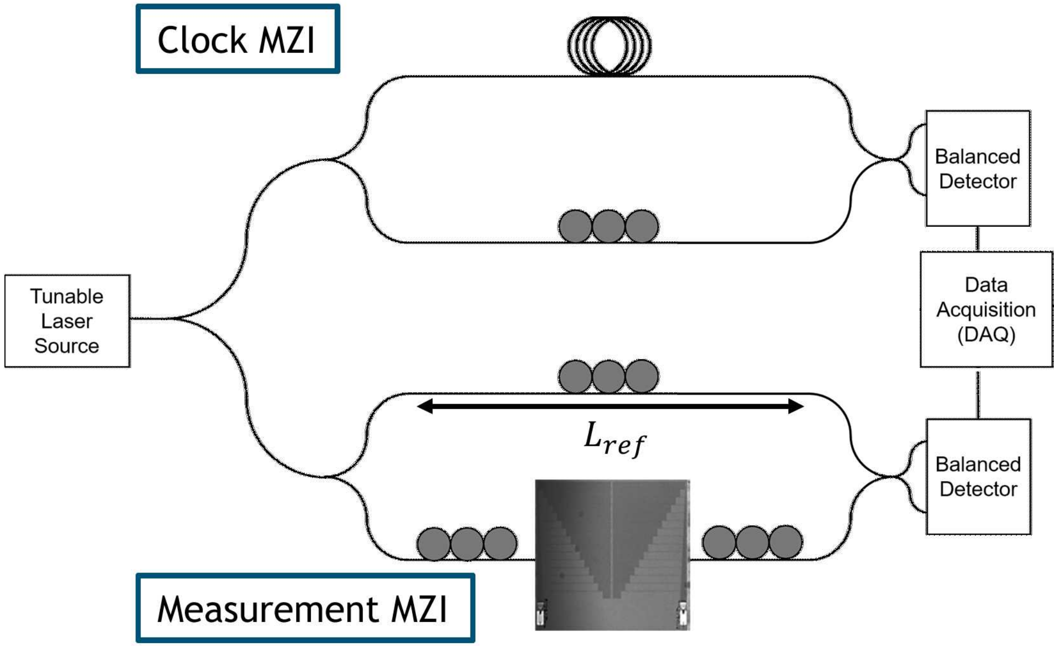


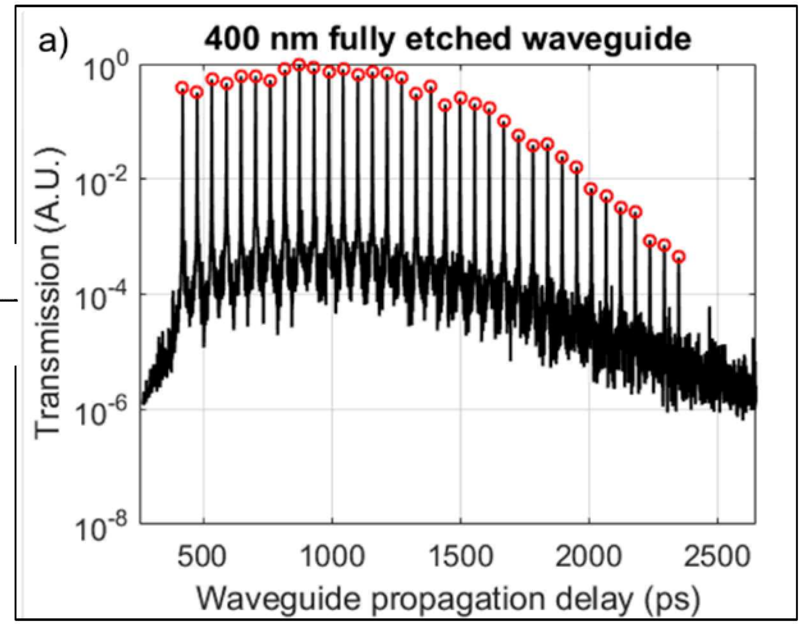
Silicon Photonic Arrayed Waveguide Structure



Serpentine waveguides allow for large path-length differences in low footprint.

Swept-Wavelength Interferometric Measurements





$$I(\nu) - I_{ref} = I_0 \sum_{m,k}^{M} e^{\xi_m + \xi_k} \cos\left[\frac{2\pi\nu n_g(\nu)}{c}(m-k)\Delta L\right] +$$

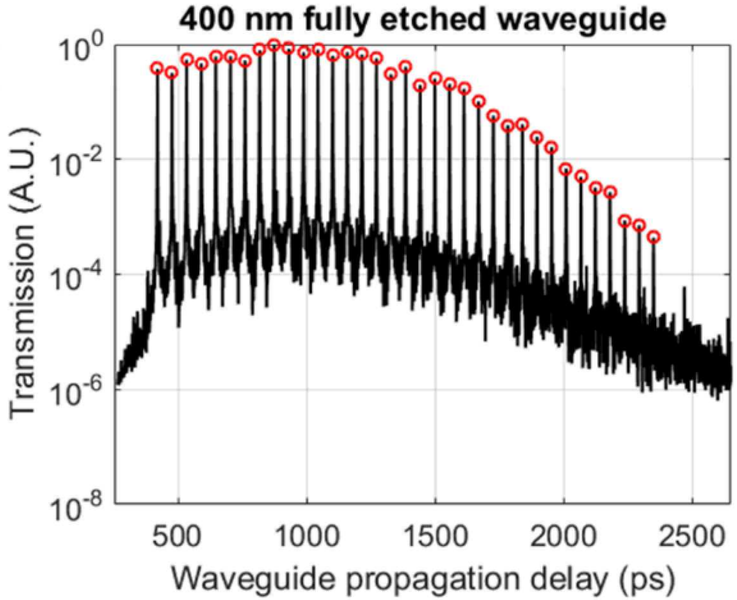
$$2\sqrt{I_{ref} I_0} \sum_{m}^{M} e^{\xi_m} \cos\left\{\frac{2\pi\nu}{c}\left[n_g^{ref}(\nu) L_{ref} - n_g(\nu)(L_0 + m\Delta L)\right]\right\}$$

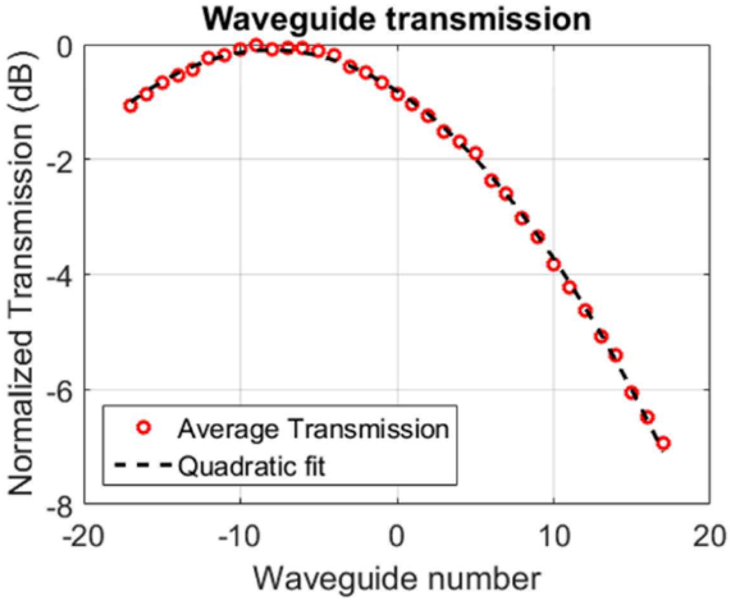
← Interference between arrayed waveguides with one another

← Interference between arrayed waveguides and reference arm of measurement interferometer

Gehl et. al., **Accurate photonic waveguide characterization using an arrayed waveguide structure, 2018**

Propagation Loss Extraction





Interference between arrayed waveguides and reference arm of measurement interferometer →

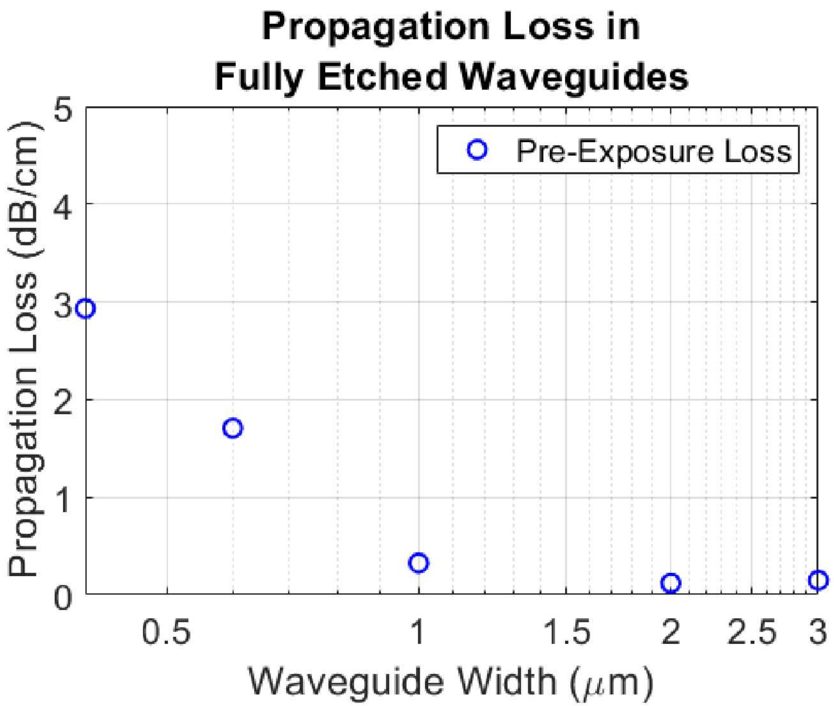
$$I_{int}(\nu) = 2\sqrt{I_{ref}I_0}\sum_m^M e^{\xi_m}\cos\left\{\frac{2\pi\nu}{c}\left[n_g^{ref}(\nu)L_{ref} - n_g(\nu)(L_0 + m\Delta L)\right]\right\}$$

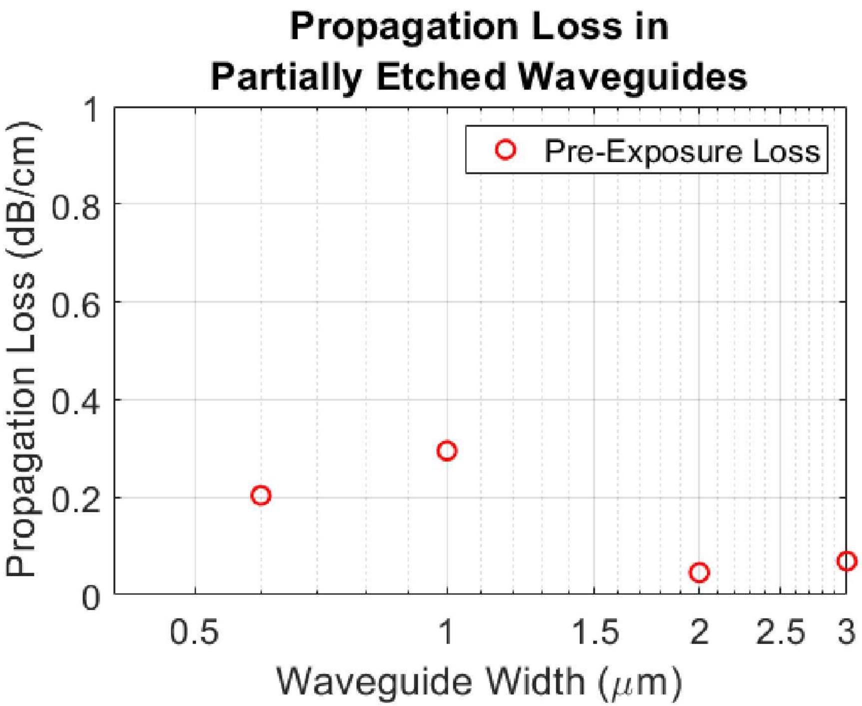
Amplitude →

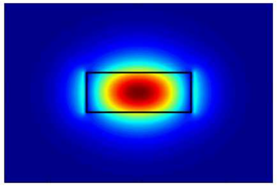
$$\xi_m = \left[\frac{\left(m - \frac{M+1}{2}\right)\delta r}{\omega(z_0)}\right]^2 - \alpha \times (L_0 + m\Delta L), m = 1,2, \dots M$$

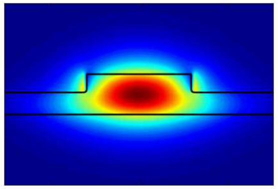
GEHL ET. AL., **ACCURATE PHOTONIC WAVEGUIDE CHARACTERIZATION USING AN ARRAYED WAVEGUIDE STRUCTURE, 2018**

Pre-Exposure Propagation Loss



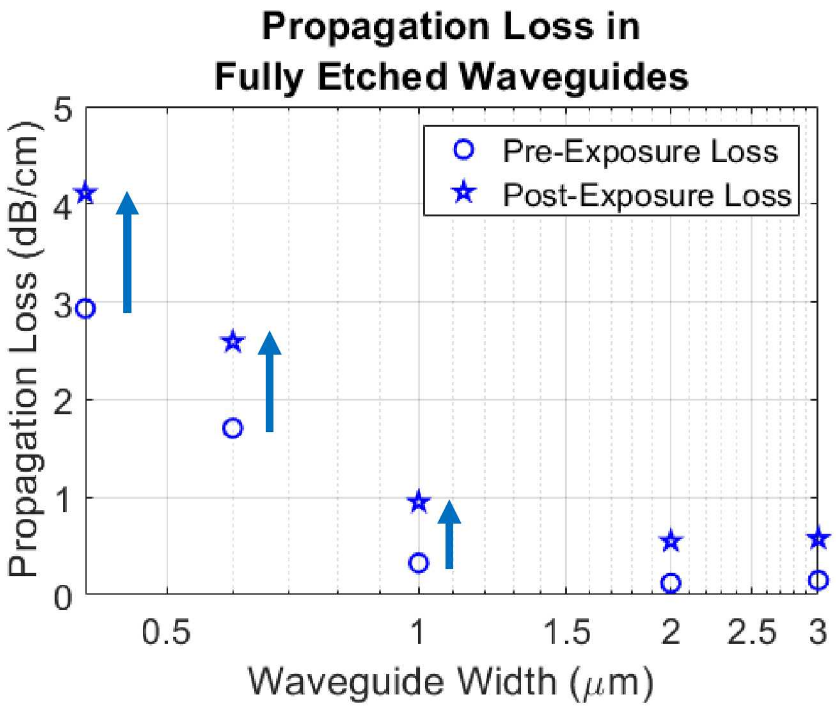


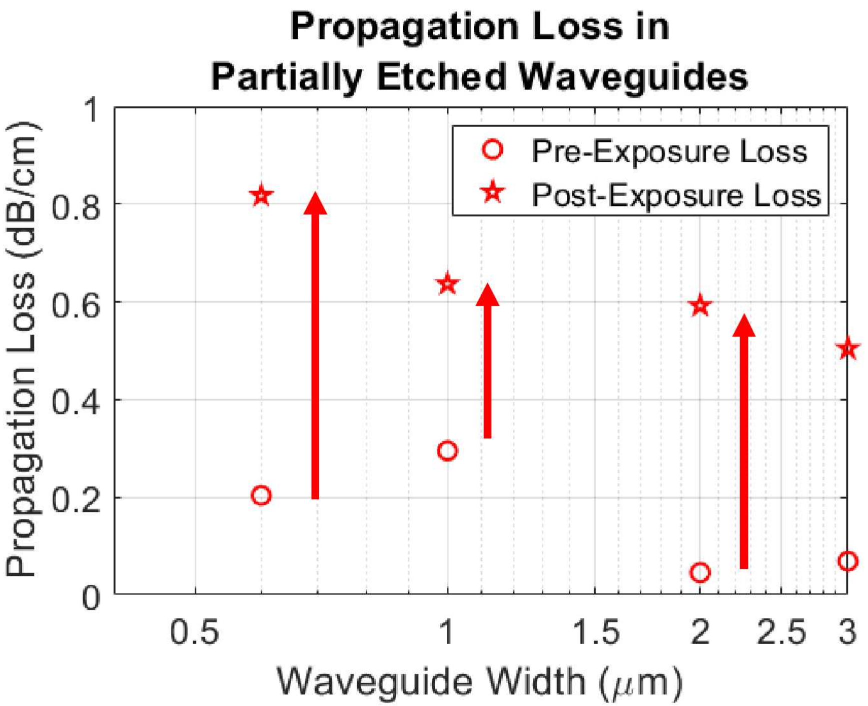


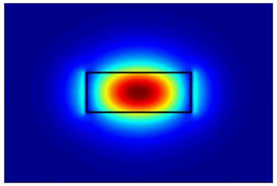


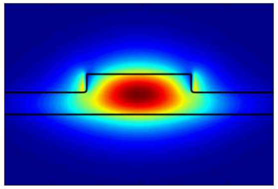
- Scattering at rough sidewalls and free carrier absorption are sources of propagation loss.
- Loss extracted at room temperature.

Propagation Loss after 100 krad Absorbed Dose



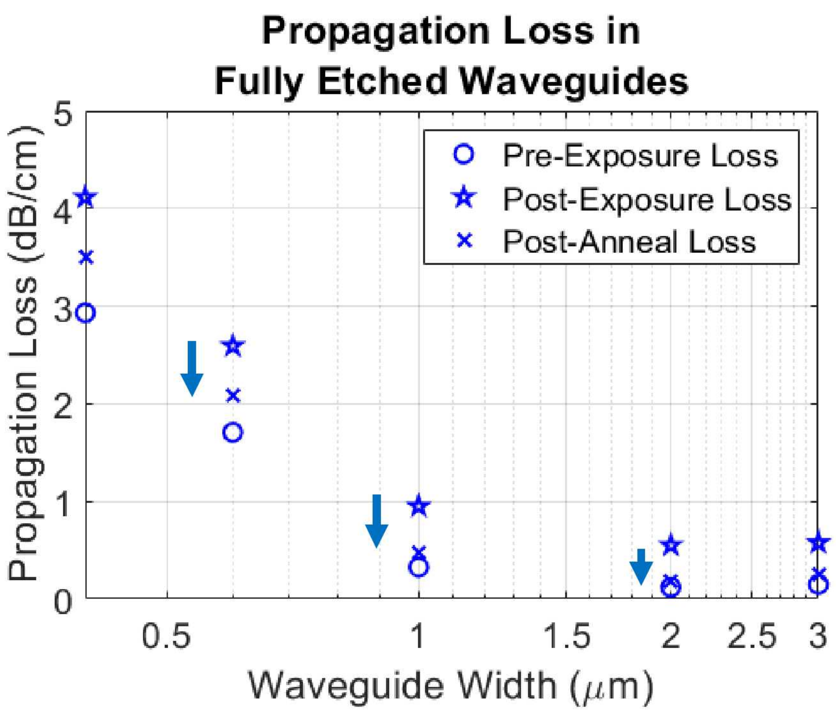


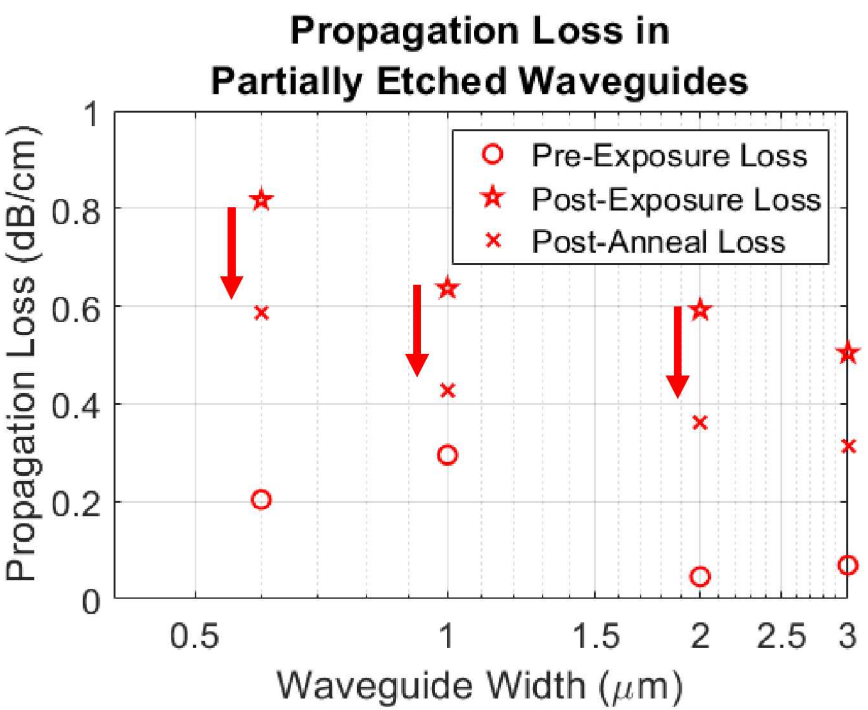


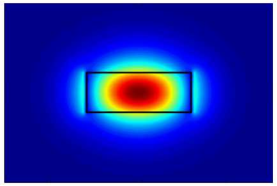


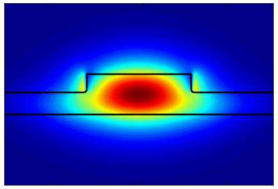
- Irradiated using ^{60}Co source (~1 MeV) at 130 rad/s dose rate for a time such that total absorbed dose is 100 krad.
- Samples temperature maintained at room temperature.
- **Slight increase in propagation loss due to increased free carrier absorption.**

Recovery of Waveguide Performance Using Heat Treatment





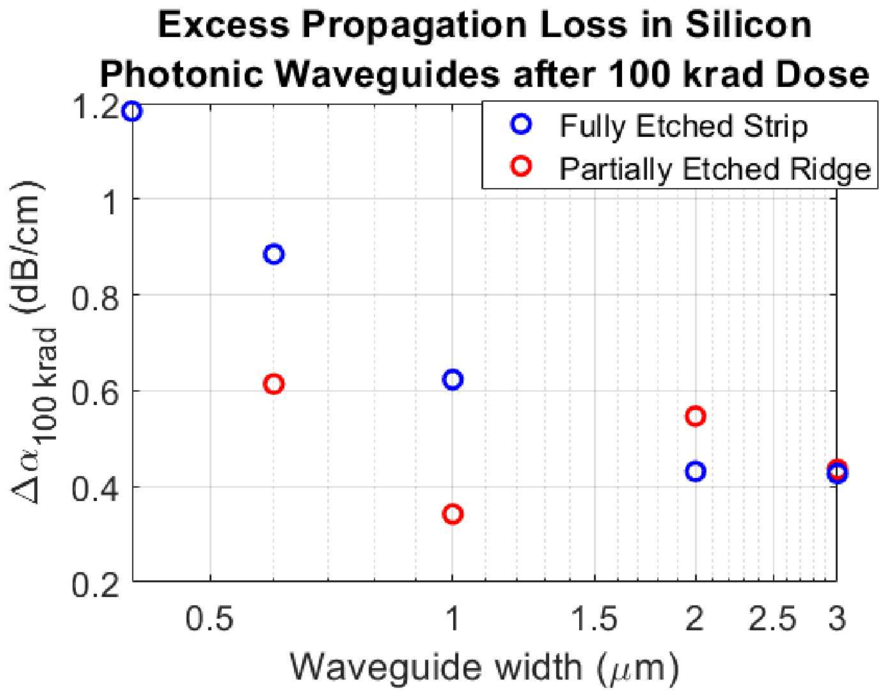


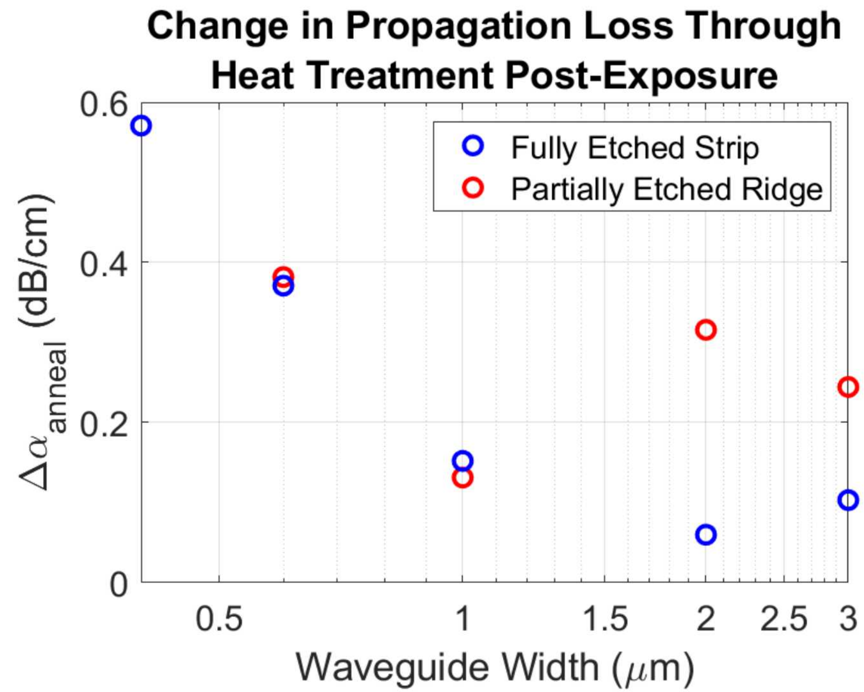


- Samples annealed at 200° C for two hours.
- Neutralization of radiation induced charge attributed to hydrogen passivating dangling interface bonds and defects in SiO_2.*
- **Reversal of performance degradation caused by induced radiation.**

T. MA ET. AL., IONIZING RADIATION EFFECTS IN MOS DEVICES AND CIRCUITS, 1989

Viability of Silicon Photonics in Harsh Environments





- Increase in propagation loss, but minimal system impact.
- Induced radiation damage can be improved through annealing.
- As low as ~ 1 dB increase in propagation loss post heat treatment for cm length waveguides.
- Intelligently design waveguides to be more resilient to γ-radiation.
- **Conclusion: Sandia's silicon photonic platform suitable for space applications.**

Wednesday, Session 13.4 from G. Hoffman: Effects of gamma radiation on active silicon photonic devices

Thursday, Session 35.4 from K. Dean: Radiation tolerant photonics at Sandia

Questions?

Nicholas Boynton nboynto@sandia.gov

References

[1] M. Zeiler et. al., Radiation-Hard Silicon Photonics for Future High Energy Physics Experiments, 2017

[2] S. Grillanda et. al., Gamma Radiation Effects on Silicon Photonic Waveguides, 2016

[3] Z. Ahmed at. al., Assessing Radiation Hardness of Silicon Photonic Sensors, 2018

[4] Q. Du et. al., Gamma Radiation Effects in Amorphous Silicon and Silicon Nitride Photonic Devices, 2017

[6] M Zeiler et. al., Radiation-Hard silicon Photonics for Future High Energy Physics Experiments, 2017

[7] N. M. Johnson et. al., Characteristic Electronic Defects at the Si-SiO2 Interface, 1983

[8] D. M. Fleetwood et. al., Unified Model of Hole Trapping, 1/f Noise, and Thermally Stimulated Current in MOS Devices, 2002

[9] R. Soref & B. Bennett, Electrooptical Effects in Silicon, 1987

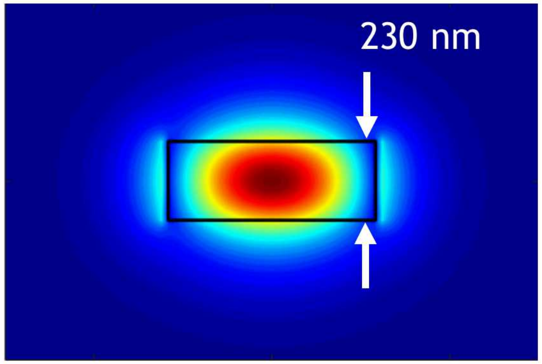
[10] M. Gehl et. al., Accurate Photonic Waveguide Characterization Using an Arrayed Waveguide Structure, 2018

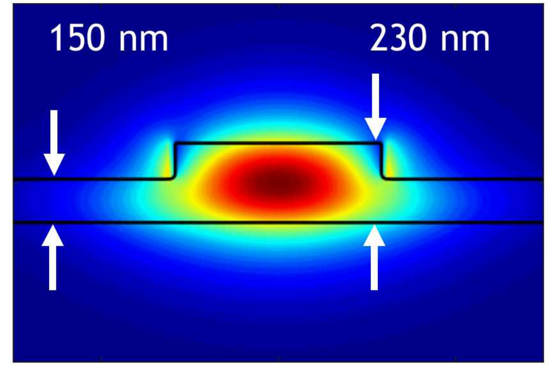
[11] J. Zhang et. al., Investigation of X-ray Induced Radiation Damage at the Si-SiO_2 Interface of Silicon Sensors for the European XFEL, 2012

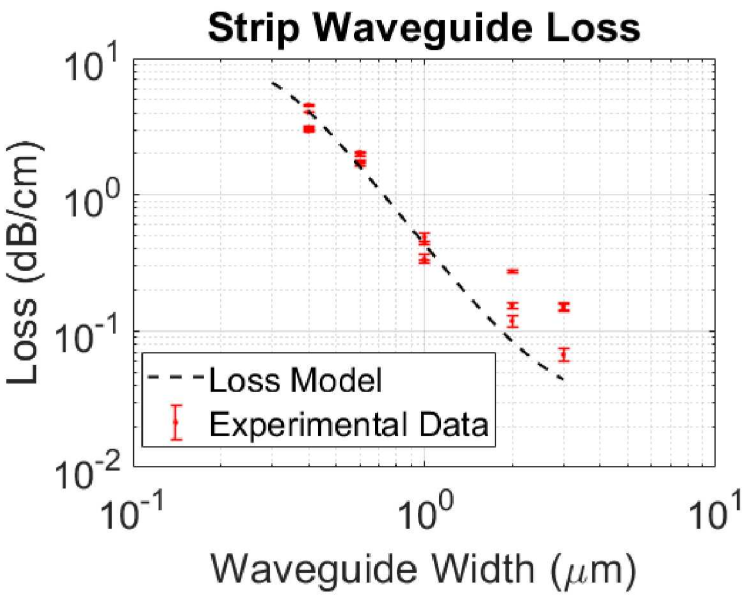
[12] P. Fernandez-Martinez et. al. Simulation of Total Ionising Dose In MOS Capacitors, 2011

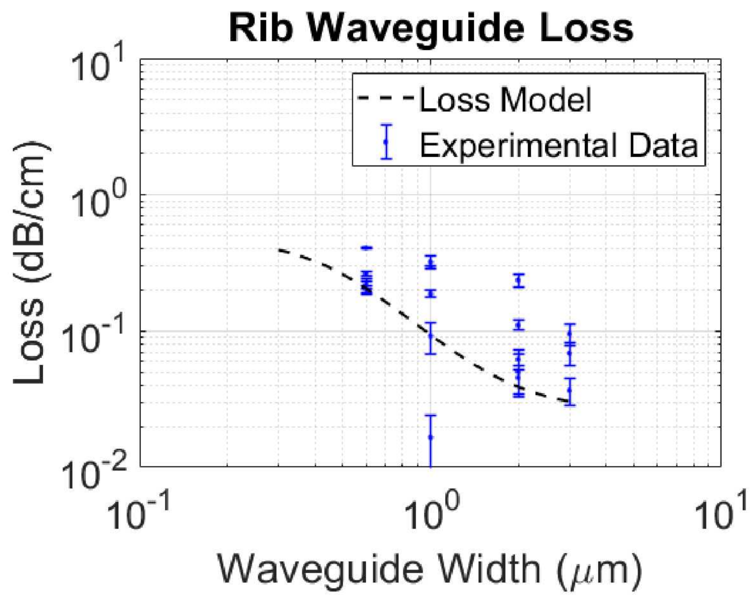
[13] T. Ma et. al., Ionizing Radiation Effects in MOS Devices and Circuits, 1989

Propagation Loss in Fabricated Silicon Photonic Waveguides







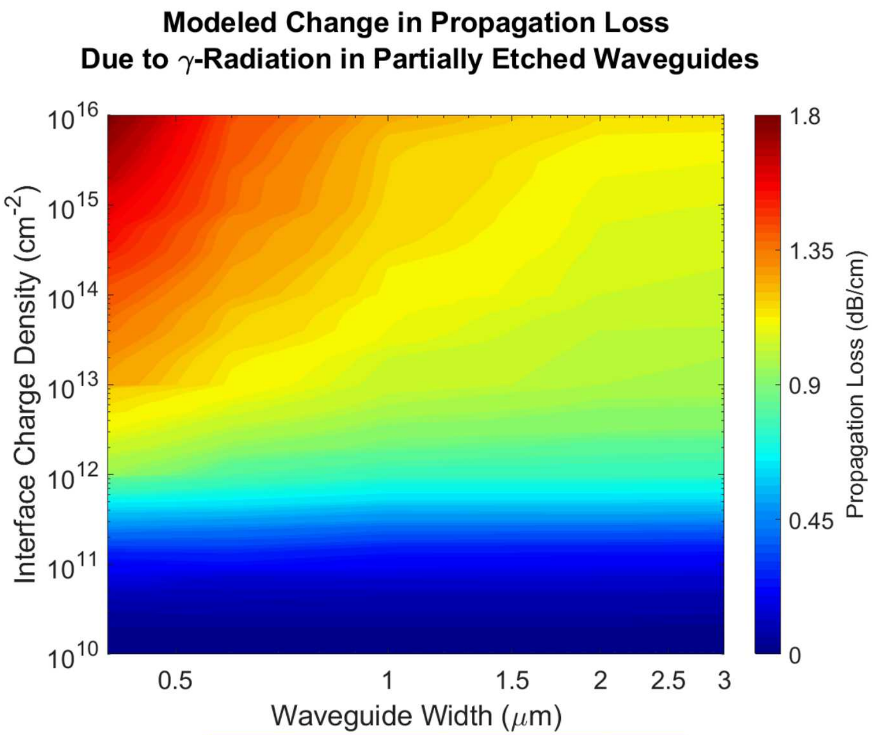


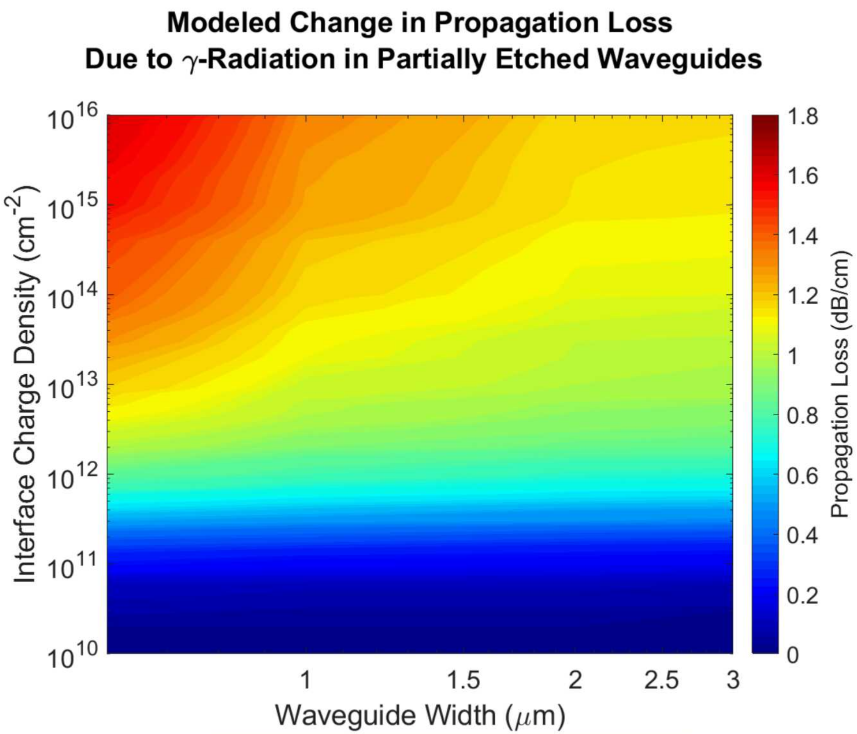
Total Propagation Loss →

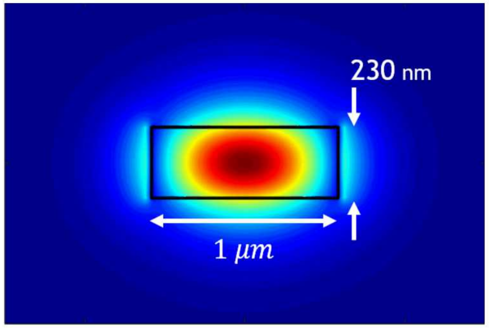
$$\alpha(\nu) = 16\frac{\sigma^2}{\sqrt{2}k_0 w^4 n_1} g(V) f_e(x,\gamma) + \delta\alpha_h \times \Gamma_{Si},$$

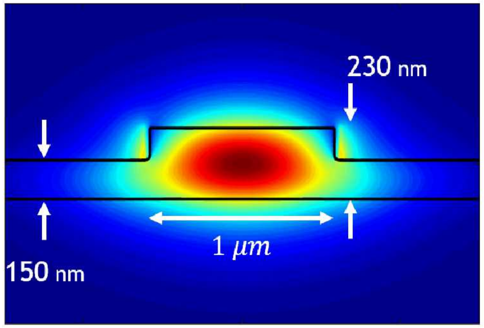
GEHL ET. AL., **ACCURATE PHOTONIC WAVEGUIDE CHARACTERIZATION USING AN ARRAYED WAVEGUIDE STRUCTURE, 2018**

Free Carrier Absorption in Silicon





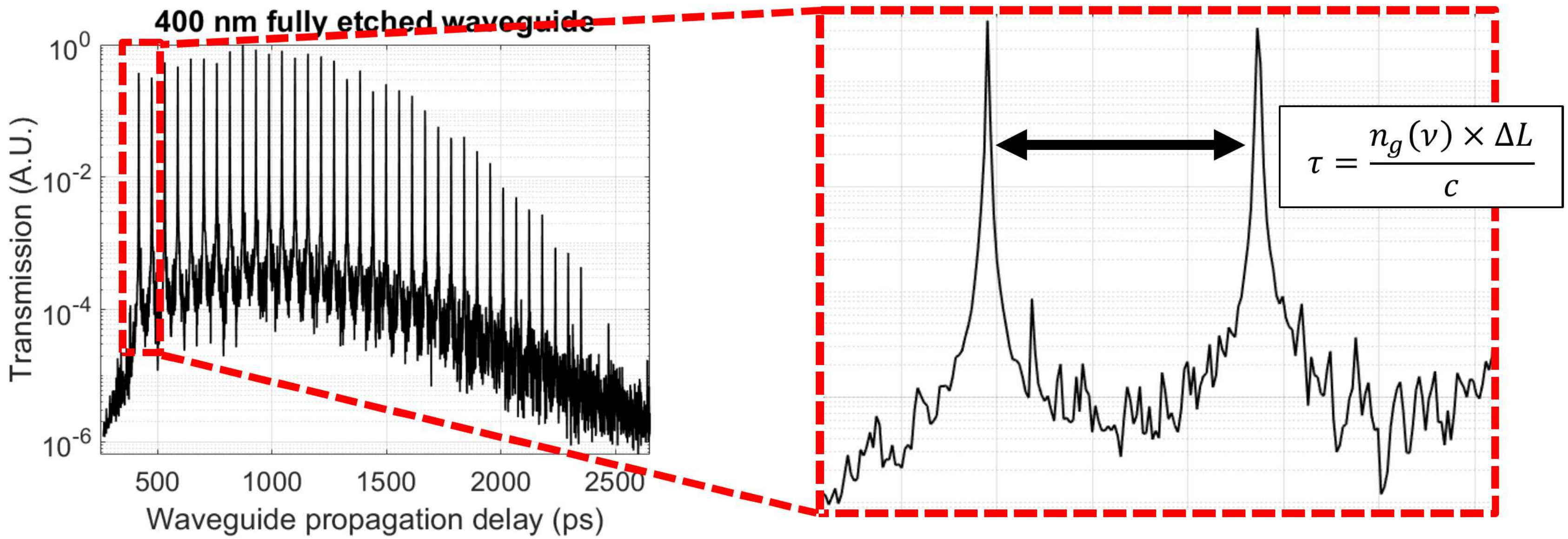


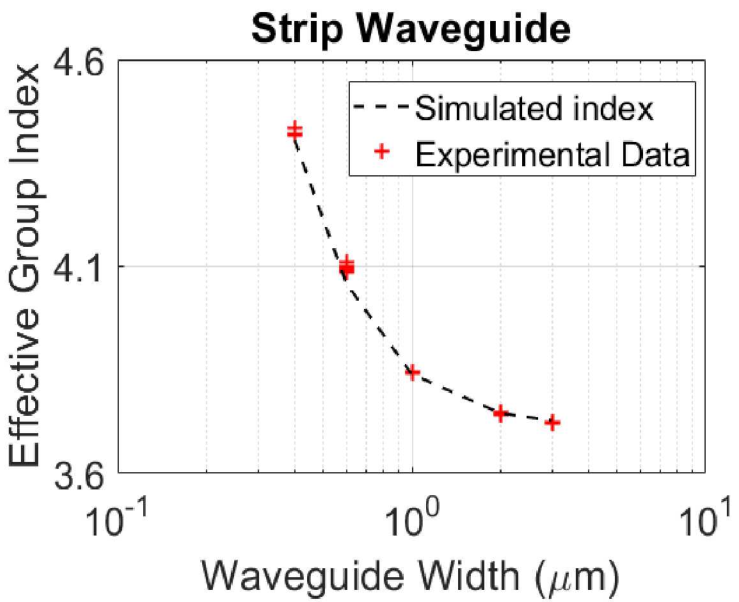


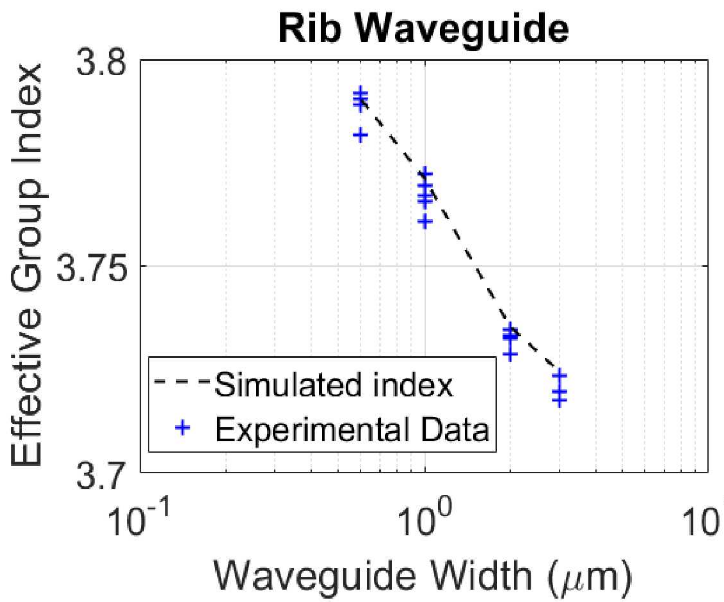
$$\delta\alpha_{Si}(\lambda = 1550\ nm) = 6 \times 10^{-18}\Delta N_H + 8.5 \times 10^{-18}\Delta N_e$$

R. SOREF & B. BENNETT, ELECTROOPTICAL EFFECTS IN SILICON, 1987

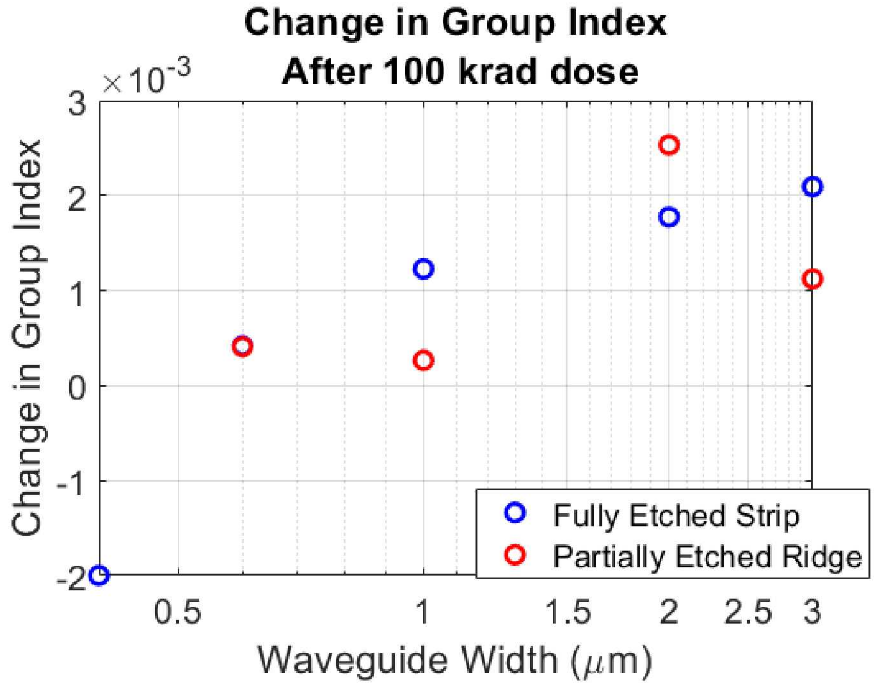
Group Index Extraction



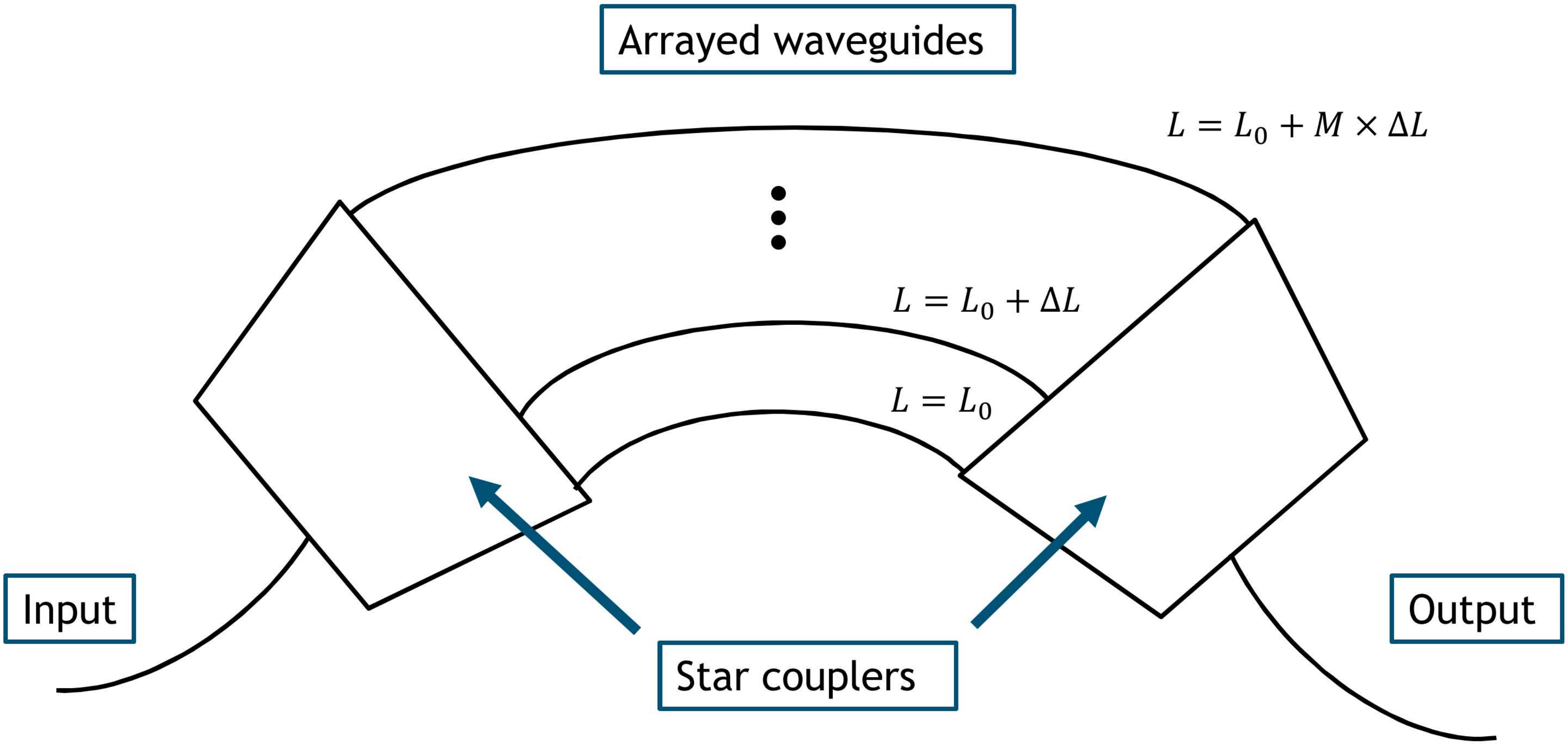




Change in group index



Arrayed Waveguide Structure for Loss Characterization



- Total foot print is $4 \times 4\ mm^2$ (17 arrayed waveguides) and $8 \times 8\ mm^2$ devices (35 arrayed waveguides) fabricated.
- Partially etched rib waveguides and fully etched strip waveguides studied of various widths.

Theory

Transmission through m^{th} arrayed waveguide →

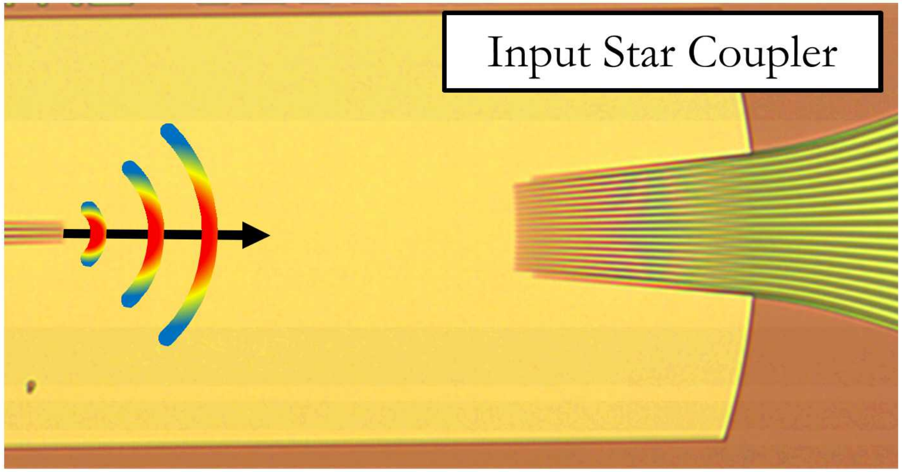
$$t_m \propto e^{\xi_m(\nu)+j\phi_m(\nu)}$$

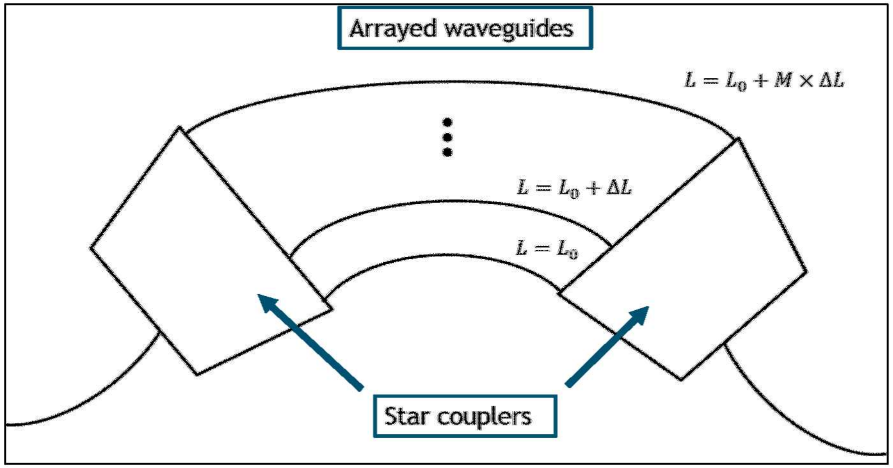
Amplitude →

$$\xi_m(\nu) = \left[\frac{\left(m - \frac{M+1}{2}\right)\delta r}{\omega(z)}\right]^2 - \alpha(\nu) \times (L_0 + m\Delta L), m = 1,2, \dots M$$

Phase →

$$\phi_m(\nu) = \frac{2\pi\nu n_g(\nu)}{c}(L_0 + m\Delta L), m = 1,2, \dots M$$





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Amplitude →

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Phase →

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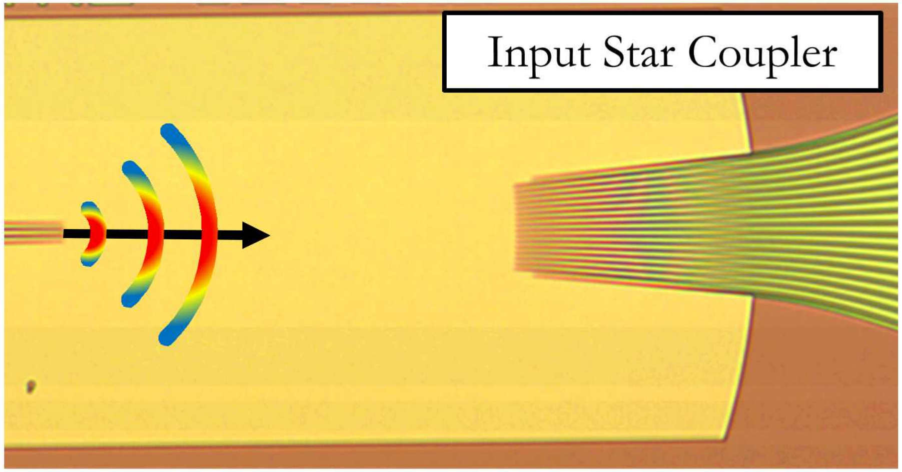

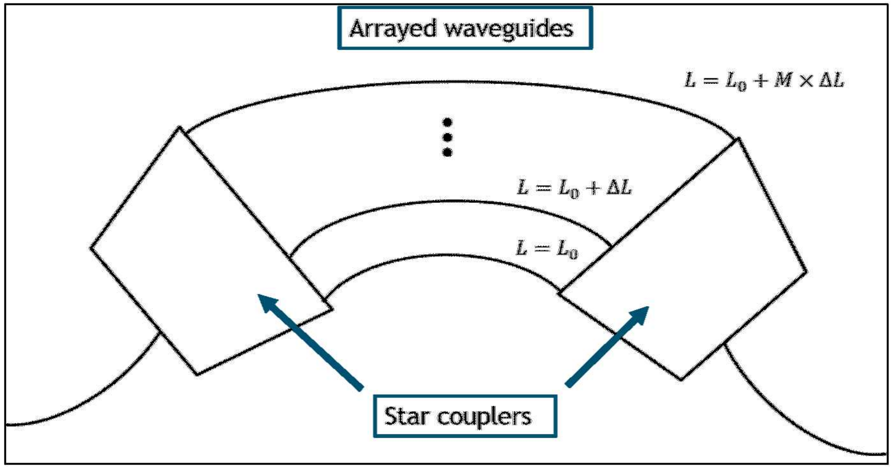

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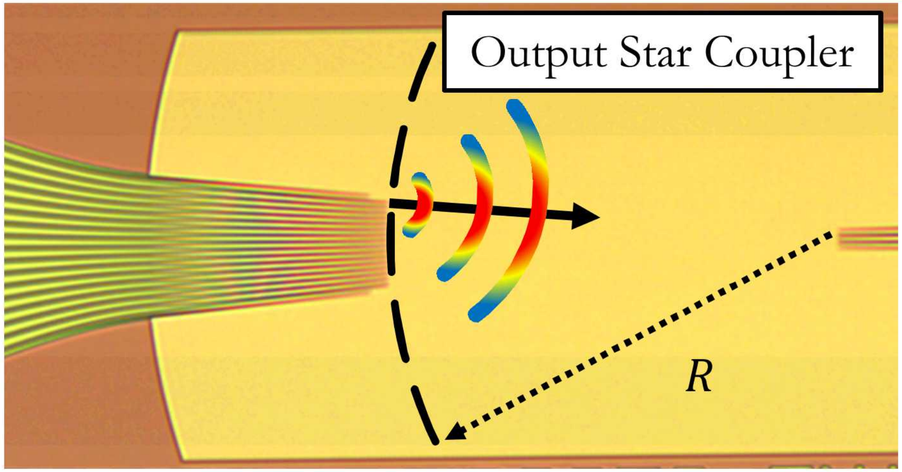
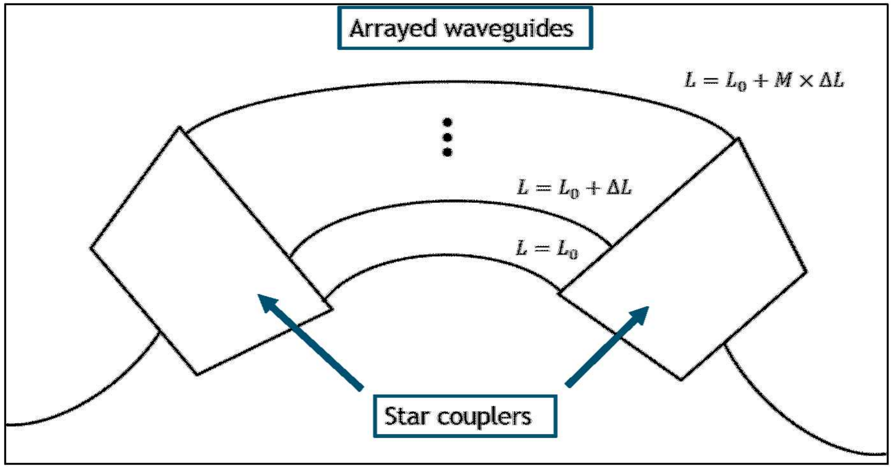
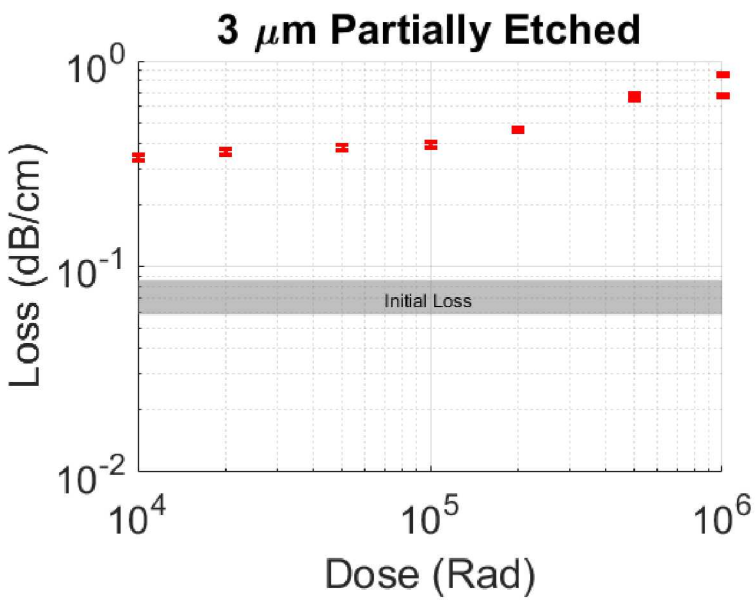
Amplitude → $$\xi_m(\nu) = \left[\frac{\left(m - \frac{M+1}{2}\right)\delta r}{\omega(z)}\right]^2 - \alpha(\nu) \times (L_0 + m\Delta L), m = 1,2, \dots M$$

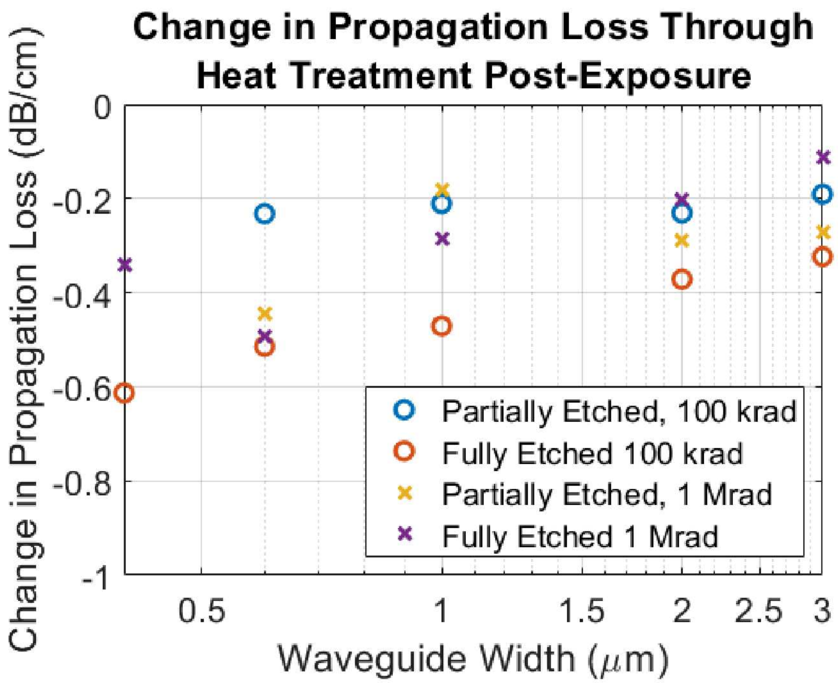
Phase → $$\phi_m(\nu) = \frac{2\pi\nu n_g(\nu)}{c}(L_0 + m\Delta L), m = 1,2, \dots M$$

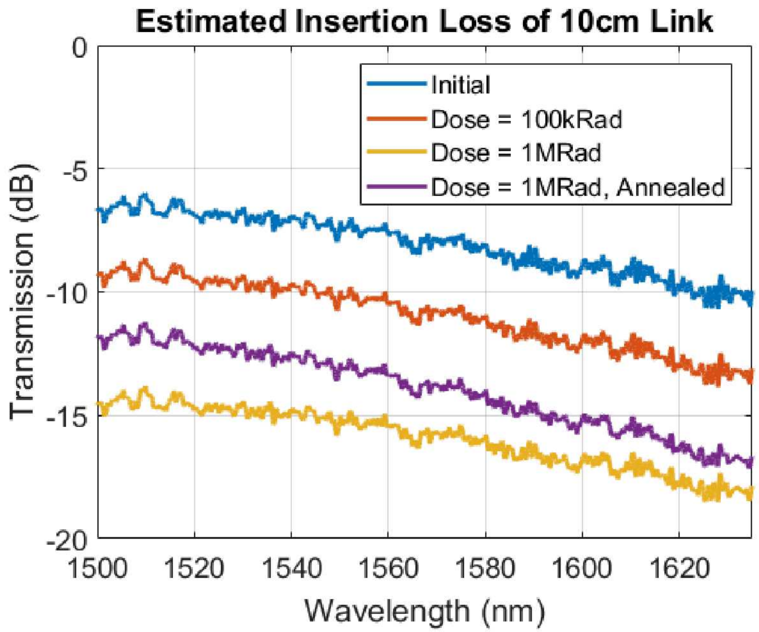




Viability of Silicon Photonics in Harsh Environments







- Anneal at 200° C for two hours
- Thermal detrapping of holes in SiO_2
- Anneal of dangling Si bonds
- Increase in propagation loss, but not significant enough to lead to device failure.

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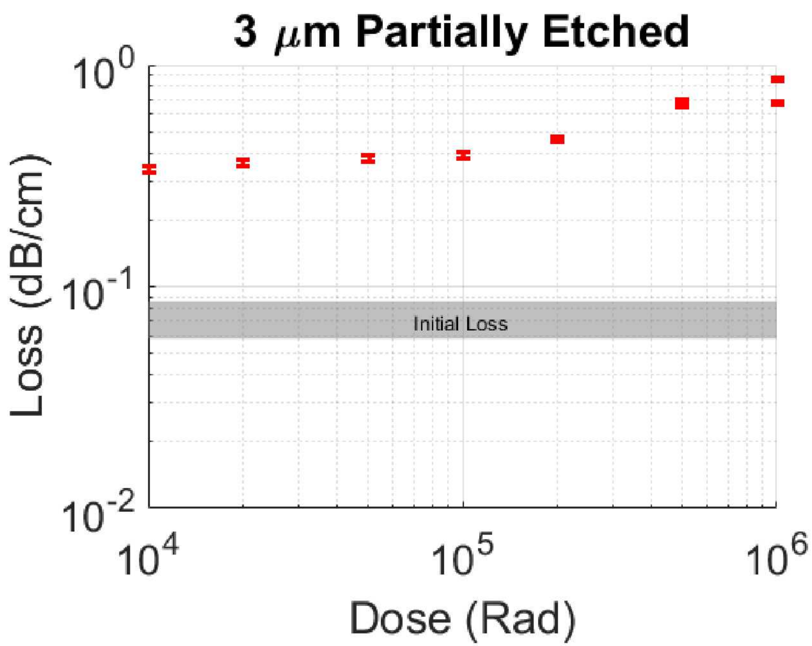
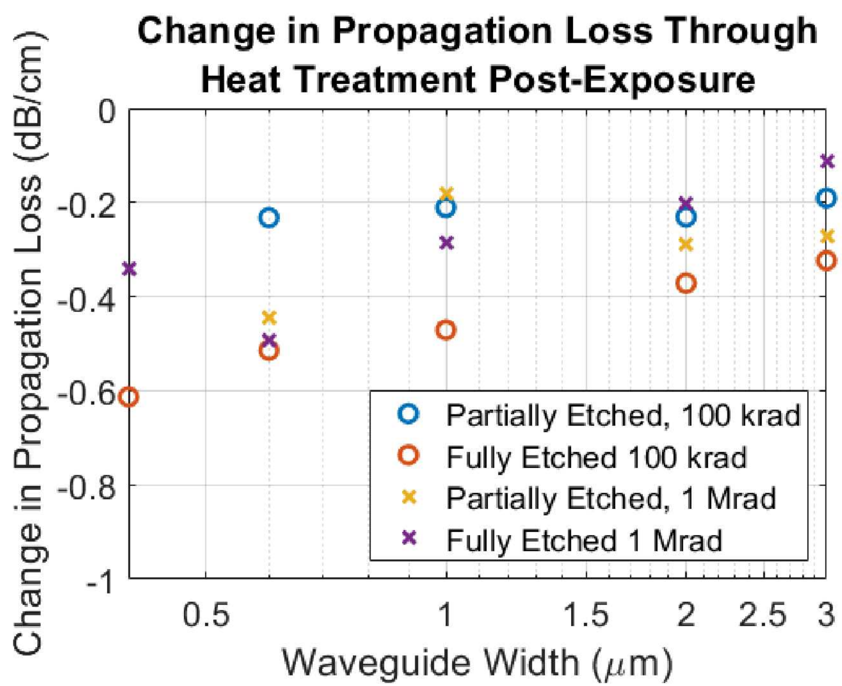
Viability of Silicon Photonics in Harsh Environments





- Anneal at 200° C for two hours
- Thermal detrapping of holes in SiO_2 and anneal of dangling interface bonds
- Increase in propagation loss, but not significant enough to lead to device failure.

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